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Urban energy generation: The added value of photovoltaics in social housing

A.S. Bahaj*, P.A.B. James

Sustainable Energy Research Group, School of Civil Engineering and the Environment, University of Southampton, Highfield, Southampton, SO19 1BJ, UK

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Abstract

Social housing offers an alternative for low-to-medium income families and keyworkers (teachers, nurses, and police). In the United Kingdom (UK), this fairly priced, rental accommodation is normally owned by housing associations. This paper explores urban energy generation (micro-generation) focussing on photovoltaics (PV) and how its generated electricity can be used to provide added value in terms of demand reduction and contribute to a reduction in fuel poverty. It presents the results associated from in-depth monitoring of nine low-energy social housing units equipped with PV systems commissioned in 2004 in the South of England, UK. We report on energy load profiles and relate these to occupier behaviour and any changes in consumption that occur. The results highlight the impact of micro-generation showing a close correlation between occupant behaviour and energy consumption. Increased energy awareness can lead to changes in the way energy is used, reducing overall consumption but 'education' must be sustained to ensure long-term energy reductions. The financial benefit of operating high demand electrical appliances at the peak of the solar day as opposed to in the evening when overall demand on the central grid is higher is highlighted. The paper also draws conclusions allied to the challenges that PV micro-generation technology presents in the social housing context.

Keywords: Urban energy generation; Energy tariffs photovoltaics; Building integration; Fuel poverty

*Corresponding author. Tel.: +44 23 8059 2051; fax: +44 23 8067 7519.
E-mail address: A.S.Bahaj@soton.ac.uk (A.S. Bahaj).

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1. Introduction

Urban energy generation at the small scale can be defined as micro-generation and is simply the generation of energy—heat or electricity—by individual buildings or small groups of buildings. The technology that provides this energy distinguishes itself from that traditionally used in that it gives occupiers the responsibility to produce energy to partly sustain their homes or buildings. Micro-generation technologies include photovoltaic (PV) installations, micro-combined heat and power systems, micro-wind, solar thermal systems, fuel cells and micro-hydro systems. There is a huge potential to utilise this type of technology in the urban built environment not only to satisfy demand and provide decentralised generation but also to help tackle fuel poverty and achieve reduction in emissions.

In the United Kingdom (UK), the Government has set short term targets of reducing the country's carbon dioxide emissions to 20% below 1990 levels by 2010, to achieve 10% of electricity generation from renewable sources and to install 10 GW of combined heat and power capacity by the same year. In response to these targets and the provisions in the Energy White Paper (and subsequently, the UK Energy Act 2004), there have been two primary initiatives aimed at encouraging the installation of microgeneration technology—Clear Skies2 (solar thermal), and the Major Photovoltaic Demonstration Programme with total funding over 4 years of around £42.5 m [1]. In essence, the emphasis of these programmes is that if buildings can be made energy efficient and produce their own energy this will not only have a real impact on overall energy demand but also in tackling climate change.

In addition to the known environmental benefits, the impact of urban renewable energy generation on the occupier of a building can provide another impetus to justify its use and added costs. If one considers PV, as an example, there are now many exemplar buildings in which this technology fulfils the role of multifunctional building component [2–4]. Specifically, the use of PV laminates to provide weather protection, solar gain/solar

shading control and also generating electricity. This is a testament to the flexibility of PV as a micro-generation technology in the built environment.

PV technology can also be considered in terms of both its direct and indirect energy benefits [5]. The direct benefit is clearly one of sustainable electrical power generation and also in financial savings. Indirect benefits are more subtle and span 'softer' issues such as pride in housing and increased energy awareness to technical issues such as generation at point of use, grid strengthening and, as will be highlighted here, the potential for demand reduction. It can also be argued that the use of PV when combined with occupier perception and behaviour can result in further environmental benefits or additionality that has not been previously reported. The linkage of occupier perceptions, energy generation and utilisation through surveys and system monitoring, as will be discussed in this paper, can highlight social, environmental and economic benefits aspects that are worthy of consideration when studying energy in buildings—especially in social housing.

2. Social housing

The cost of housing in the UK is extremely high. This applies equally to both rented accommodation and homes for ownership. This cost creates major problems as many critical public sector staff such as teachers; nurses and police are not able to afford housing close to their place of work. In addition, a significant proportion of the population either on low salaries or on social benefits cannot compete or afford such expensive housing. As an example, the average price of a house in the South East of England, in the third quarter of 2005 was £186,000 [6]. This figure excludes the central and outer metropolitan regions of London. A 25-year mortgage on such a property would require an annual salary of £43,000 (£1 = 1.7US$) and a monthly repayment in excess of £1000 at an interest rate of 5%. For a large proportion of the population such a combination of income and monthly payment is not a realistic proposition. In April 2004, the Nationwide building society for example stated that 'price growth … is clearly unsustainable given that affordability has become so stretched, buyers on average earnings are struggling to get a foot on the property ladder' [7]. In London house prices have risen by 44% since 2000, raising the average house price to 8.8 times the average salary. Affordability of housing in the capital; according to the 2004 Annual London Survey [8] is the number one ranked impact on the quality of life. The result of the lack of affordability in housing in London and the South East in particular is that there is a strong demand for high quality, fair priced rental accommodation and this is generally provided by Housing Associations in the UK [9].

2.1. Fuel poverty

At present, UK domestic fuel bills are dominated by the winter heating season with a typical 3 bedroom domestic house consuming approximately 20,000 kWh per annum for space heating and 3000 kWh of electrical demand [10]. Fuel poverty is defined by the UK government as 'households being defined as fuel poor if, in order to maintain a satisfactory heating regime, they were required to spend more than 10% of their income on all household fuel use. This assumes that a satisfactory heating regime is one where the main living area is at 21 °C, with 18 °C in other occupied rooms' [11]. There is also the issue of fuel poverty which in the UK, remains a real problem in the social housing sector with winter fuel bills in particular being a cause for worry amongst many tenants. Whilst

building integrated photovoltaics (BiPV) do not address the winter fuel issue directly they can provide a significant contribution towards the annual electrical demand and an overall reduction of the fuel burden.

3. Urban energy generation (micro-generation)

Micro-generation—small scale electrical power generation at point of use—is seen to offer a range of potential benefits to both the homeowner and the network operator. Small scale PV such as that used in buildings (BiPV) can be termed as a micro-generation technology. It can be combined with other electrical power generating technologies such as wind (micro-wind) and micro combine heat and power (micro CHP) to arrive at what can be termed as urban energy generation technologies. Micro CHP is distinct in that if offers the potential for grid operator controlled use and so could be potentially used to offset traditional plant infrastructure. However, this is highly dependant on how power is delivered and whether distributed generation within a centralised grid system is possible. In addition, successful operation of micro-generation, particularly at a high level of grid penetration, requires a clear understanding of the loads involved. Precise monitoring is required that can provide informative feedback to the occupier and to the utility.

3.1. Micro-generation technologies—perceptions

The highly visible nature of PV and the direct and clear coupling between the resource (sunlight) and the level of power generation makes this microgeneration technology one of the best in terms of raising understanding of energy use. Whilst other technologies such as micro-wind or micro CHP are at present considered more economically favourable than PV [12] they do not provide the same level of interaction with the homeowner. Micro CHP in particular risks being treated in the same way as a normal boiler within a house. Whilst this should be the target mode of operation (i.e. blind to the homeowner), this may not deliver the best environmental performance. If applied without detailed consideration of the best mode of operation the significant emission (carbon dioxide) savings that such a system should offer (~20–30% for a typical 3 bed detached house in UK) can easily be lost [13]. As for micro-wind generators, the power output is proportional to the cube of incident wind speed which makes generation difficult to assess by the tenant, especially from within a house, where the building structure further reduces the ability to perceive wind speed [14]. PV in contrast is far simpler and its output is tuned to the highly sensitive human perception of daylight. In addition, for non-tracked PV where BiPV is almost exclusively applied, the potential generation profile is fixed in time determined by the orientation of the array. Unlike micro-wind, this enables a homeowner to anticipate power generation.

4. Tariffs and subsidies

In terms of economics, energy efficiency and sustainability of domestic microgeneration technologies in the UK, it is generally very important to avoid export of generated electricity (or heat) [5]. In general, the tariff that a homeowner is paid for export of electricity to the grid is a fraction of the import cost. Typically, in the UK for example, a homeowner would be offered payment at ~£0.02/kWh for electricity export, compared to

being charged ~£0.07/kWh for import. This poor tariff may also be provided in conjunction with dual metering charges, which further erodes the benefits of the electricity produced by the PV system.

Although a variety of green tariff financing schemes now exist in the UK, the best economic arrangement available is generally one where the homeowner is paid for generation rather than export. This is possible in the UK due to the establishment of a government co-ordinated scheme, known as the Renewables Obligation Certificate or ROC [15]. The ROC scheme provides a supporting subsidy to enable the expansion of renewable energy generation by forcing electricity distributors to purchase renewable energy at a similar price to traditional generation. The scheme is aimed primarily at large scale wind (both on and off-shore), which has an installed capacity of ~1300 MW, in the UK (November 2005 [16]). The ROC subsidy is market driven and is currently offered at around £45/MWh. When applied to domestic PV, the ROC is offered at around £0.04/kWh [17]. The governing relationship in terms of financial benefits for a micro generation within domestic housing is given by

$$V_{\mathrm{H}} = \alpha \mathrm{PV}_{\mathrm{GEN}} + \beta A_{\mathrm{EXP}}, \tag{1}$$

where V_{H} (£/kWh) is the value to household of electricity generated and used within the home, $\mathrm{PV}_{\mathrm{GEN}}$ is the PV generated electricity (kWh), α negotiated renewable energy generation subsidy (α~£0.04/kWh), β (~£0.07/kWh) is chargeable cost to consumer for imported energy and $\mathrm{A}_{\mathrm{EXP}}$ represents the avoided export (kWh) = avoided import. The avoided export is highly dependant on householder behaviour. In essence $\beta.A_{\mathrm{EXP}}$ represents the cost of importing unit electricity from the grid.

5. Electricity generation and demand

In the future, the advent of variable domestic electricity price tariffs (price rises and falls with demand during the day, following the centralised generation tariff) will increase the benefit of avoided export and enhance the use of more pro-active energy management schemes within buildings or houses.

As can be seen from Eq. (1), the advantage of a generation tariff rather than an export one is that there is a financial benefit to the homeowner in trying to avoid export of electricity from the home. In essence, any electricity, which is exported to the grid in many cases is 'lost' or of very little value compared to imported electricity. Furthermore, if load matching can be achieved whereby generated electricity is used within the home, from Eq. (1), the 'effective value' of the PV generated electricity rises to £0.11/kWh ($= \alpha + \beta$) for a typical UK domestic billing arrangement.

A normal domestic electrical load profile does not, in general, provide a good match with generation. Typically, there is a high electrical demand in the morning at breakfast and in the late afternoon/early evening at the time of dinner [11]. Clearly this will be out of phase with, for example, generation from a south facing PV array. A variety of factors serve to modify this load profile and these include: number of household occupants, age, gender, time of the year, occupation, income, and weather profile. Even for identically constructed houses there can be huge variations in energy demand driven solely by the behaviour of the occupants. As will be shown later, our study of nine identical houses for example, shows that the highest energy-consuming house typically used three times that of the lowest one.

Load matching can be applied to minimise import/export and therefore obtain the maximum value for the on-site electrical generation within a house. Consider a south facing, roof-mounted array on a house located on the time meridian. On a sunny day at noon (GMT), the output of the array will be at its peak. Providing that occupiers are informed, load matching of PV is in principle, relatively easy for a homeowner to achieve with small changes in daily routine. High electrical demand appliances such as dishwashers, tumble dryers or washing machines should ideally be operated at the peak of the solar day. Electrical timers on appliances or perhaps some intelligent control may be required, if, for example, the house is unoccupied during the day. Some modern PV inverters and data loggers support dedicated load management, setting the time of day and minimum array power conditions to allow connection of a specific load to the grid [18]. This type of control will be extremely useful to implement especially in solar radiation-rich countries. This could take the form, for example, of an intelligent consumer unit which senses significant export from a dwelling and selectively connects circuits within the house. However, at present, this is very rarely used and could be difficult to implement successfully in countries such as the UK where the daily solar resource is unpredictable due to cloud cover. Therefore, more sophisticated generation and load management control systems with perhaps small-scale storage may be needed to fulfil this task.

6. Energy analysis in a social housing scheme

The thrust of this work is based on a recent social housing development located on the western side of Leigh Park in Havant, Hampshire. Leigh Park, built in the 1950s, was, at the time, Europe's largest social housing overseen by a local authority, but with the 'right to buy' many of the properties are now privately owned. The site is bounded by a school to the north, residential properties to the west and south and industrial units to the east. Before being developed this site was a car park used by the local industrial units for staff and visitor parking, and hence is considered as a brown field site. The scheme was developed by Hermitage Housing Association [19] working closely with the Local Authority, Havant Borough Council [20]. The houses are located in Havant, near Portsmouth on the South Coast of the UK (longitude 0.98 °W, latitude 50.8°N). Seven of the houses are identical in construction with two additional south facing ground floor flats or apartments built for the benefit of mobility-impaired tenants (Fig. 1).

The following sections report on a study of electrical energy flows in the nine, low energy social houses described above. In particular, due to the presence of full monitoring, the analysis will centre on electrical generation through PV and electrical energy demands within the houses. The PV systems were funded under the UK Government's Major PV Demonstration Programme mentioned earlier [1].

6.1. Sustainability issues

At a very early stage it was agreed this development should take the form of a sustainable housing scheme incorporating as many environmental features as possible. The development achieved an "excellent" eco- assessment SAP ratings [21], between 102 and 108. Whilst there has obviously been a cost premium with this project ~15% extra, the

Fig. 1. West facing array on low energy eco-homes, H7 and H8, New lane, Havant.

scheme has proved very successful. Such a high rating was achieved by incorporating the following features:

- Floors, walls and the roofs are all very highly insulated. Insulation to the walls is recycled newspaper 140 mm thick sprayed between the timber studs. All properties have warm roof construction with 190 mm of insulation roof panels.
- In general the timber is used throughout from sustainable sources with Forest Stewardship Council Certification.
- Solar evacuated tubes preheats the water prior to being heated by the highly efficient gas boilers.
- Rainwater is harvested.
- Passive ventilation to kitchens cloakrooms and bathrooms is arranged.
- Water conservation equipment is used.
- High-efficiency low-emission balanced flue gas boilers provide heating to the underfloor heating systems.
- Low energy fluorescent light fittings are used throughout.
- Sun rooms arranged to the rear of all properties.
- Waste recycling is provided.
- PV systems are used for generating electricity with two way metering.

6.2. *PV systems*

Each house has an identical PV system consisting of two SMA-SWR700 string inverters [18] each connected to a string of nine BP585L roof mounted laminates [22,23]. The rated output of the PV system of each house is 1530 Wp. There are six south, two west and one

east facing array. The arrays are inclined at 45°, with no shading from surrounding buildings or trees (Fig. 1).

All tenants were provided with a home PV user guide to explain the system installed on their houses. This guide included information on selecting the best import–export tariff regime for their needs and how to avoid export of electricity to maximise financial return. In addition the performance of the systems on a month-by-month basis was published on a web site to enable system performance and house electricity usage to be observed. A kWh display meter was installed in the entrance hall of each house to show cumulative yield of the PV electricity generated since commissioning.

6.3. Energy assessment

An assessment of energy generation, consumption and export is described in the following sections for a period of one year. For each house, the time integrated electricity import, export and onsite generation is recorded every 5 min along with environmental parameters such as irradiance and temperature. The electrical generation of the six south facing PV systems is very similar, with typically less than 1% variation in the monthly energy yield (Fig. 2). This indicates the consistency in the manufacture and operation of both the PV laminates and in particular the inverters used [23].

The predicted annual yield Y for a South facing PV system can be estimated as follows:

$$Y = \mathrm{PR}\ G_{\mathrm{I}} G_{\mathrm{STC}}, \tag{2}$$

where G_{I} is the average plane of array irradiance (kWh/m^2/yr), G_{STC} is the nominal array power rating at Standard Test Condition (STC) in (kWp) and PR is the performance ratio

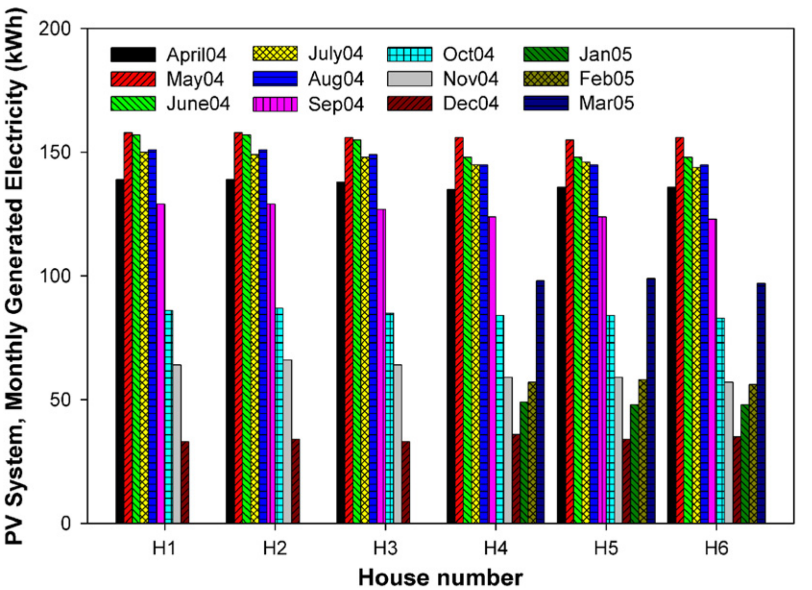

Fig. 2. Month-by-month generation for the six identical south facing, 1.53 kWp PV arrays, Havant, UK, 12 month period April 2004–March 2004.

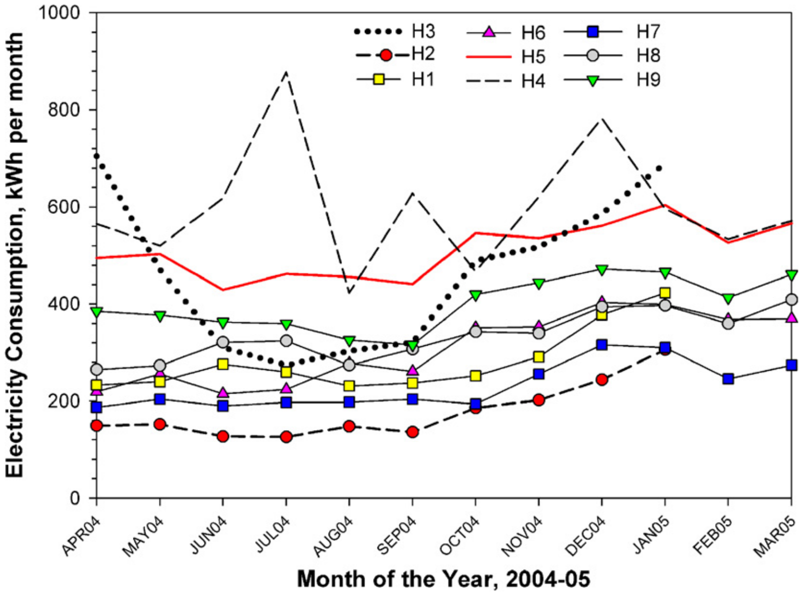

Fig. 3. Comparison of the electricity consumption (kWh per month) for the nine houses (H1,…,H9) at New Lane, Havant, April 2004—March 2005. Incomplete monthly data sets for houses H1, H2 and H3 are omitted.

defined as the ration between actual performance and that expected from nominal rating (dimensionless). For appropriately designed systems PR$\geqslant$70%.

Therefore for the systems installed in Havant, the predicted yield/system is given by

$$Y = 0.70 \times 1200 \times 1.53 = 1285\,\text{kWh}.$$

The average measured yield or electrical energy generated by a PV South facing system for the 12-month period described in this paper was 1235 kWh. This is within approximately 0.04% of the predicted yield given by (2).

The monthly energy consumption of the nine houses is shown in Fig. 3. The variation in energy consumption between these houses is quite dramatic, especially when considering that the houses are low energy by design and build. House four (H4) is of particular interest in this respect. The corresponding percentage of PV electricity generation, which is exported to the grid from each house, is shown in Fig. 4. House five (H5), has a significantly lowest percentage of export (~25%) than any of the others, who export between 40% and 70% of generated PV electricity. What is surprising here is that some households, despite very high electricity consumption still export a significant fraction of the generated PV electricity (Fig. 4).

If the month of August 2004 is considered in detail, Fig. 3 shows that houses H4 and H5 both consumed approximately 450 kWh of electricity. The corresponding percentage export for houses H4 and H5 (Fig. 4) was 49% and 28% respectively, for a PV generation level of ~145 kWh (Fig. 2). In comparison, house H2, which had the lowest demand of ~148 kWh in August 2004, exported ~66% of electricity generated by the PV system.

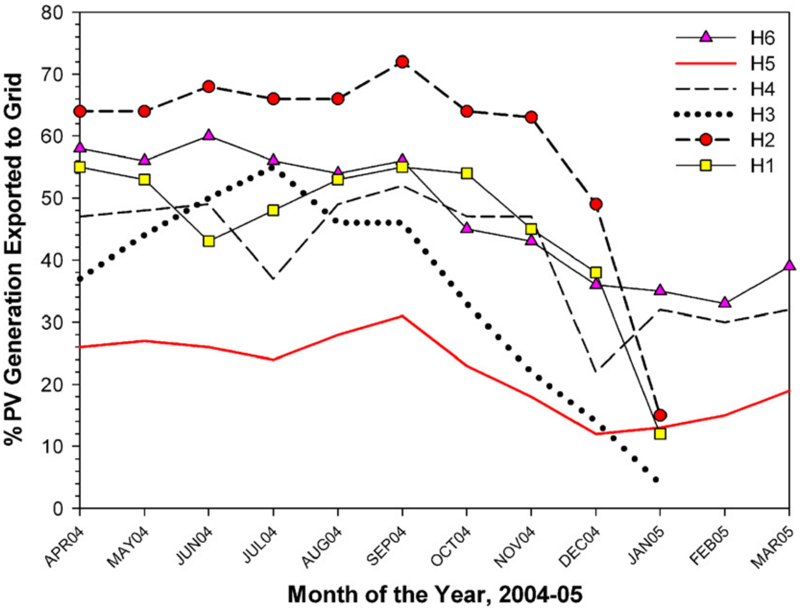

Fig. 4. Comparison of the percentage of PV system electricity generation, which is exported (kWh per month) for the six South facing houses (H1,…,H6) at New Lane, Havant, April 2004—March 2005. Incomplete monthly data sets for houses H1, H2 and H3 are omitted.

6.4. Anatomy of consumption

In order to identify why there is such a variation in energy export and consumption it is necessary to understand the load profiles of the typical tenant.

A scatter plot of the level of electricity consumption during August 2004, over 5 min periods in (Wh) for houses H2, H4 and H5 is shown in Figs. 5–7, respectively. Overlaid on the graphs is the measured generation profile of the PV system during a sunny day in August (04/08/04). The peak output of the PV system occurs just after 12:00 (GMT), due to the longitude of the site, 1° west of the Greenwich Time meridian.

Low demand electricity consumption user (H2): Fig. 5 shows the electricity consumption distribution for house H2 for August 2004. Baseline electricity demand is approximately 20 Wh per 5 min period (~240 W). There are clear breakfast and evening meal demand peaks but in general there is very limited potential for load matching. This is reflected in the PV export figure for the month of ~65%.

Peaky, high demand electricity consumption user (H4): House H4 shows a very peaky electricity profile with prolonged periods of high electricity consumption in both the morning and early evening. Such high electricity consumption corresponds to the use of high power, long cycle devices (washing machine, dishwasher, tumble dryer) in addition to far more transient loads (kettle, cooker). It is interesting to note that there is a close correlation between occupier behaviour and energy consumption (Fig. 8.). Without the presence of PV and the data from its associated monitoring such behaviour would have been overlooked. Clearly, there is scope for load shifting, with the morning loads in particular missing the peak of the solar day by around 4 h.

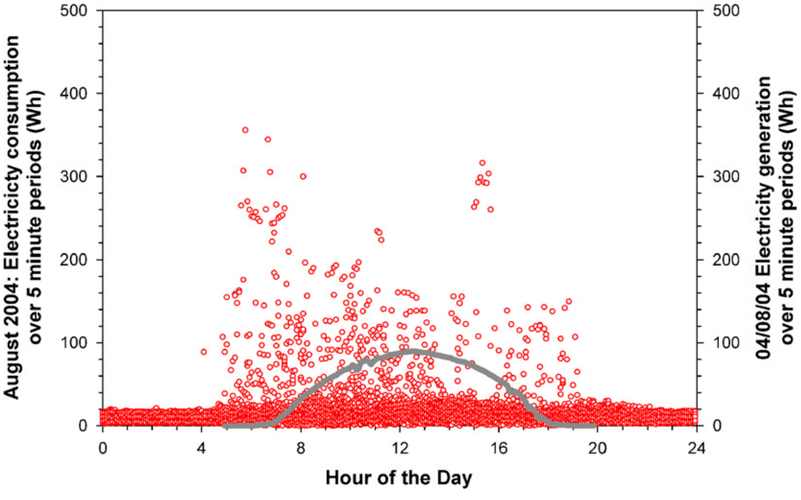

Fig. 5. Electricity consumption (Wh time integrated 5 min intervals) for house H2, August 2004. Overlaid with PV generation profile for a sunny day (04/08/04).

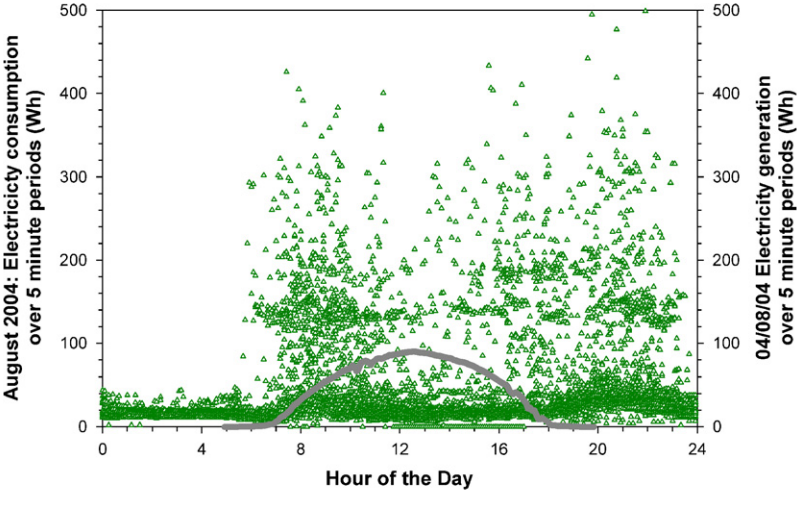

Fig. 6. Electricity consumption (Wh time integrated 5 min intervals) for house H4, August 2004. Overlaid PV generation profile (04/08/04).

High base load, high demand electricity consumption user (H5): The base load level of house H5 varies between 20 and 45 Wh per 5 min period, corresponding to a power demand of 240–540 W. This is approximately double that of house H4 (120–240 W), even though both houses have the same monthly electricity consumption. House H5 therefore, shows very limited potential for load shifting towards the peak of the solar day. High demands at 08:00 and 17:00 GMT correspond to fixed load times of breakfast and evening meals.

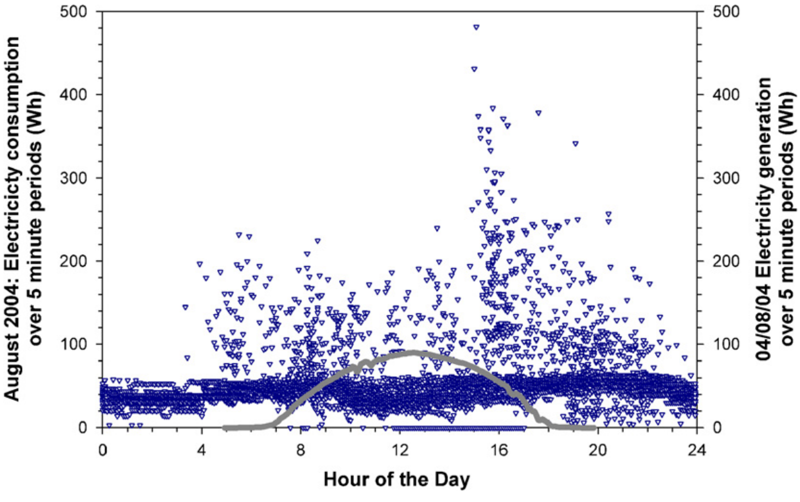

Fig. 7. Electricity consumption (Wh time integrated 5 min intervals) for house H5, August 2004. Overlaid PV generation profile (04/08/04).

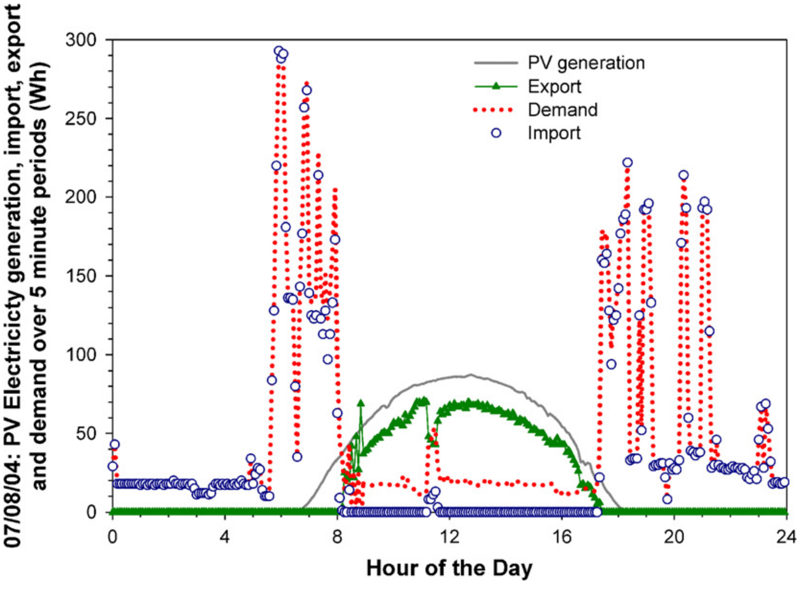

Fig. 8. PV generation, import, export and consumption profiles for house H4 for the 7th August 2004.

The consumption profiles discussed above are indicative of the daily profiles of the three houses. These profiles show that the lower export of house H5 relative to H4 is due to a higher base load demand rather than any form of load matching.

As can be seen from Fig. 3, there is a general trend of increased electricity consumption over the 12-month period studied. If a first order fit is made to the electricity consumption profile of each house (Fig. 3) a neutral gradient (0) would be expected, if over the entire year there was no net change in electricity consumption. It is somewhat disappointing that

only one of the nine houses (H4) shows a slight negative gradient and this is for the property with the highest electricity consumption.

There are probably a range of factors which are causing a rise in consumption levels. During site visits, the authors have noticed an increase in proliferation of consumer electronic devices within the properties, notably large screen televisions and computers with 'always on' broadband connections. Several houses have also added a second chest freezer, sometimes placed in the sun room. Others have exchanged the low energy lighting with what they perceived to be aesthetically pleasing but less efficient counterpart. Such changes are driving up the electricity consumption and merely serve to highlight that users are key to the success of a low energy building. The profile of the three high-energy consumers shows a rise of 3% over the 12-month period. In contrast the six low-to-medium energy consumers showed an average increase of 34%.

7. Added value of PV in social housing

The PV generation, import, export and consumption profiles for house H4 over a 24 h period (07/08/2004) is shown in Fig. 8. Over 70% of the PV generated electricity is exported from the house during this day. This is despite the fact that, over the entire day, the overall demand is 69% higher than the 8.2 kWh (integrated area under the bell curve) of electricity generated by the PV system. If the base load demand is accounted for it is clear that there are virtually no 'active loads' between 08:00 and 19:00 GMT. The breakfast period of electricity consumption (05:45–08:00) corresponds to 4.7 kWh, of which 4.0 kWh of usage (~1.8 kW continuous) is above the base load level. Therefore, demand can be matched by the PV generator if the occupier is advised to shift these demands closer to the solar noon.

In terms of economic benefits, the financial payback time for domestic, grid connected PV systems does not usually take into account the supplementary benefits that the PV system provides. If we consider the 1.5 kWp PV system, installed on each house and Eq. (1). For such houses in the UK, having south facing, 45° pitch roof mounted and Irradiance of 1200 kWh/m^2/yr, the following applies:

- PV generated energy = PV_{GEN} = 1235 kWh.
- Typical annual electricity consumption for a 3 bedroom house (no electrical heating) ~2500 kWh.
- Generation is not really in phase with demand for a domestic house. Predicting avoided import, A_{EXP}, in Eq. (1) is difficult.

The question here is "can one maximise the financial benefit to the home owner?" Table 1 represent some scenarios for optimising such an income to the household based on various export philosophies.

However, experience indicates that the level of export, from energy aware, low energy users with a reduced base load demand can be as high as 70% [5]. In this case, the financial return is ~£39 per annum less than the ~£114 per annum of high demand users.

As discussed above, to generate electricity, the PV system can bring a heightened awareness of the concept of electricity consumption and cost. Considering house H4 above, if for example, 50% of its electricity consumption could be shifted to the PV generation period export over the entire day would be reduced by a third on a sunny day.

Table 1
Scenarios of householder income from PV generated electricity based on export philosophy

	Best case[a] {Eq. (1)}	Typical case[b] {Eq. (1)}	High demand user	Low demand user'
Export condition	No export of PV generated electricity $PV_{GEN} = A_{EXP}$	50% export of PV generated electricity $A_{EXP} = 0.5\ PV_{GEN}$	25% export	70% export
Income to householder	£136	£98	£114	£75

[a]Best case estimated as follows: $V_H = (1235 \times [4/100]) + (1235 \times [7/100]) =$ £136.
[b]Typical case estimated as follows: $V_H = (1235 \times [4/100]) + (1235 \times [50/100] \times [7/100]) =$ £93.

Furthermore, in a social housing context, there may be a small number of tenants who utilise a disproportionate level of energy—generally as a result of a lack of understanding. Analysis of electricity consumption in the New Lane, Havant development indicated that three of the nine houses show very high levels of electricity consumption (>5000 kWh per annum) [5]. The PV systems of these three houses can be used as an education tool to try and reduce/modify the way in which energy is used in these households.

7.1. Estimating the 'added value of PV' through education of high-energy domestic users

The electricity saving associated with having a PV installation is a combination of the energy generated by the system and the impact of the PV system on occupier behaviour. Therefore, on average, a PV system in this social housing context can be considered to achieve an energy saving as follows [5]:

$$S_{PV} = PV_{GEN} + [N_{HIGH}/(N_{HIGH} + N_{NORMAL})]E_{RED}, \tag{3}$$

where S_{PV} is the electricity saving associated with the PV in social housing (kWh/house/yr), PV_{GEN} is the average annual electricity yield of a PV system in housing development (kWh), E_{RED} is the possible reduction in consumption by a high electricity usage 'uninformed user' house as a result of raised awareness of energy (kWh), N_{HIGH} is the number of high electricity usage 'uninformed user' houses and N_{NORMAL} is the number of normal electricity usage 'informed user' houses.

In the case of the New Lane development, one can estimate electricity savings based on Eq. (3) taking into account consumption behaviour of the tenants and the potential for reductions. The average annual electricity yield of a PV system in the housing development in kWh (over the nine houses) PV_{GEN} is $\sim$1200 kWh per annum. The highest measured annual electricity consumption was that of house H4 at 7200 kWh. The H4 tenant stated that they used 'intensive' or 'hot wash cycles' on their dishwasher, tumble dryer and washing machine as a matter of course believing that they produce the best treatment cycle without having an appreciation of the energy requirement of their selection.

During April 2004 for example, the combined energy use of the dishwasher (39 kWh), tumble dryer (121 kWh) and washing machine (58 kWh) was monitored and represented 37% of electricity consumption. Such a usage pattern, if reflected over the entire year would correspond to an annual demand of $\sim$2500 kWh. The selected, intensive mode of

such appliances is typically 30–50% higher than 'eco' or 'quick' low-energy modes. Smarter selection of the operating mode of these appliances could realise a reduction in electricity consumption of ~30%. This corresponds to a reduction in the annual electricity consumption of ~10% ($2500 \times 0.3 \sim 800$ kWh). If such a shift in behaviour could be realised across the three high-energy users (H3, H4 and H5) the electricity saving attributable to the PV system, S_{PV}, would be $[1200 + (3/9) \times 800] = 1470$ kWh per household per annum. This also means that the effective energy yield of the PV system across the entire housing scheme has been increased by 20%. The major benefit is that for the high user, this saving is equivalent to the annual yield of a 2.5 kWp PV system rather than the actual 1.5 kWp installed PV capacity on the house.

7.2. The reality of 'added value of PV' through education of high-energy domestic users

In early 2004, informal discussions were held with tenants to discuss energy consumption, generation and export profiles. As a result of this information exchange, a marked reduction could be seen in the consumption profiles of two of the three high-energy user tenants (Fig. 3, H3 and H5 April 04–July 04). Although some of this reduction may be attributed to the change of the season (extended daylight hours), the reductions achieved far outweigh what would be associated with this demand, especially with the low-energy lighting scheme used at this development. However, the change in energy usage behaviour is not sustained and within 12 months the electricity consumption is back to, or exceeds the previous level. As stated previously, for eight of the nine houses a net increase in electricity consumption is observed over the monitoring period. In early 2006, all nine houses will be offered an 'energy audit' by the research team to reinforce the 'energy message.' It is hoped that this process will reverse the significant electricity consumption increases observed over the described 12-month period.

8. Conclusions

The use of building integrated photovoltaics in social housing developments in the UK can provide a significant contribution towards the annual electrical demand and an overall reduction of the fuel burden. Active load matching can enhance the financial return to the homeowner but current tariff schemes penalise energy efficient users in comparison to their high-demand neighbours. It has been shown that for very peaky profile users, with prolonged periods of high electricity consumption in both the morning and early evening, consumption could be shifted to the PV generation period and export over, a sunny day for example, would be reduced by a third. However, for housing that shows a constant "base load" demand there is very limited potential for load shifting towards the peak of the solar day.

Our analysis indicates that there is a wide variation in the monthly energy consumption between the nine identically constructed south facing houses. Despite the financial incentive to utilise PV generated energy locally our study shows that there is little evidence of load matching or switching, especially amongst the high demand users (typical export 50% of generation). The level of export, from energy aware, low energy users with a reduced base load demand can be as high as 70%. In the future, microgeneration load matching will become increasingly important as the domestic baseload level is hopefully

reduced through reduced energy demands of domestic refrigeration (better insulated) and lower standby power consumption of consumer electronics.

Targeting of high electricity users (>5000 kWh per annum) to try and moderate their behaviour by enhancing their understanding only achieved moderate success. Significant reductions in electrical consumption in two of the three high-energy users were observed for the first few months following discussions of energy usage.

It was anticipated that the visible installation of microgeneration technologies such as PV would keep reminding occupants of the link between energy generation and consumption. The experience here indicates that this is however, somewhat wishful thinking, as the behaviour of occupants does not reflect this premise. In spite of some early success at reducing demand, within a year the consumption returned to the previous level. This highlights that on-going education and re-enforcement of the energy message must be undertaken to achieve long-term demand reduction.

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